NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3124

A METHOD FOR ESTIMATING THE EFFECT OF TURBULENT VELOCITY FLUCTUATIONS IN THE BOUNDARY LAYER ON DIFFUSER TOTAL-PRESSURE-LOSS MEASUREMENTS

By Jerome Persh and Bruce M. Bailey

Langley Aeronautical Laboratory
Langley Field, Va.

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SUMMARY

A method is presented for estimating the effect of turbulent velocity fluctuations on diffuser total-pressure-loss measurements. This method stipulates continuity of flow and is based on the assumption that the diffuser dimensions, inlet conditions, and the approximate distance from the wall, if finite, to the point of zero velocity are known, that the flow is symmetrical, and that the velocity outside the boundary layer at the downstream measuring stations is not measurably influenced by the turbulent velocity fluctuations. Only the case of the conical diffuser with incompressible flow is considered.

When the longitudinal velocity fluctuations are large, as evidenced by discrepancies between the inlet and exit weight flows, the method compensates for the discrepancies by adjusting the boundary-layer profile. Total-pressure-loss coefficients estimated by the proposed method produce substantially higher (more pessimistic) values than those obtained from uncorrected impact-pressure-tube surveys. Application of this method to the experimental data for cases of negligible weight-flow discrepancies shows that the calculated total-pressure-loss coefficient is in agreement with the experimental value.

INTRODUCTION

The extensive application of subsonic diffusers to modern aircraft powerplant installations and the desirability of effective space utilization have prompted the direction of considerable research toward developing efficient, short, wide-angle diffusers. The steep longitudinal static-pressure gradients occurring in components of this type, however, result in highly distorted boundary-layer velocity profiles at the diffuser exit. Such profiles are characterized by the presence of turbulent fluctuating velocities which may significantly affect impact-pressure-tube measurements.

Boundary-layer control devices which accelerate the turbulent exchange of momentum may intensify this effect. In the investigation reported in reference 1, in which triangular ledges were installed circumferentially in a 23° conical diffuser in an effort to increase the momentum transfer, exit weight-flow values computed from impact-pressure data were found to be 10 to 15 percent higher than those at the inlet. Consequently, values of total-pressure-loss coefficient calculated from the exit data were incorrect. A study was therefore made to determine whether the weight-flow discrepancies could be attributed to the influence on the impact-pressure measurements of the turbulent fluctuating velocities in the boundary layer.

The purpose of this paper is to present a method for estimating the magnitude of the effect of turbulent fluctuating velocities in the boundary layer on diffuser total-pressure-loss measurements. In the development of this method, continuity of flow is stipulated, and it is assumed that the inlet conditions and the diffuser dimensions are accurately known, that the flow is symmetrical, and that the velocity outside the boundary layer at the downstream measuring stations is not measurably influenced by the turbulent fluctuating velocities. Only the case of a conical diffuser with incompressible flow is considered; however, the method can be readily extended to compressible flow.

SYMBOLS

g	gravitational force per unit mass
H	boundary-layer shape parameter, δ^*/θ
h	total pressure
$\overline{h}$	mean total pressure
p	local mean static pressure
q_c	impact pressure, $\overline{h} - p$
R	radius of diffuser
r	radial distance from center line
s	distance from diffuser wall, if finite, to point of zero velocity
U	velocity outside boundary layer

u,v,w	local mean velocity components
$\overline{u'^2},\overline{v'^2},\overline{w'^2}$	mean-square components of fluctuating velocity
V^2	square of mean velocities, $u^2 + v^2 + w^2$
$\overline{V'^2}$	mean square of turbulent fluctuating velocities, $\overline{u'^2} + \overline{v'^2} + \overline{w'^2}$
W	weight rate of flow, lb/sec
y	distance from wall measured perpendicular to longitudinal axis
ρ	mass density
δ	boundary-layer thickness
δ^*	boundary-layer displacement thickness, $\int_0^\delta \left(1 - \frac{u}{U}\right)dy$
θ	boundary-layer momentum thickness, $\int_0^\delta \frac{u}{U}\left(1 - \frac{u}{U}\right)dy$

Subscripts:

0	reference station
1	diffuser inlet station
2	diffuser exit station
exp	experimental
L	linear velocity distribution
T	true

ANALYTIC BASIS OF METHOD

The efficiency of a diffuser is usually expressed in terms of the static-pressure-rise and total-pressure-loss coefficients. Both of these quantities are generally determined from a series of conventional wall static- and stream total-pressure measurements at the diffuser inlet and exit stations.

The rise in static pressure is computed as the difference between the mean static-pressure measurements at the diffuser inlet and the diffuser exit; that is,

$$\Delta p_{2,1} = p_2 - p_1 \tag{1}$$

The loss in mean total pressure between inlet and exit stations is generally determined by the following relations for symmetrical flow:

$$\Delta \bar{h}_{0,1} = \bar{h}_0 - \bar{h}_1 = \frac{\int_0^R u\left(h_0 - h_1\right) r \, dr}{\int_0^R ur \, dr} \tag{2}$$

$$\Delta \bar{h}_{0,2} = \bar{h}_0 - \bar{h}_2 = \frac{\int_0^R u\left(h_0 - h_2\right) r \, dr}{\int_0^R ur \, dr} \tag{3}$$

and

$$\Delta \bar{h}_{2,1} = \left(\bar{h}_0 - \bar{h}_2\right) - \left(\bar{h}_0 - \bar{h}_1\right) \tag{4}$$

Equations (1) and (4) are usually nondimensionalized by dividing by the inlet impact pressure q_{c_1}.

Results shown in reference 2 indicate that impact-tube measurements are influenced by turbulent fluctuating velocities. The total pressure recorded by an impact tube in an airstream containing fluctuating velocities may be expressed by the following relation (ref. 2):

$$h = p + \frac{1}{2} \rho V^2 + \frac{1}{2} \rho \overline{V'^2} \qquad (5)$$

(In this relation the static pressure is assumed to be uniform across the measuring station.) Because $\overline{V'^2}$ is always positive, the measured total pressure will always be greater than the effective total pressure by the amount $\frac{1}{2} \rho \overline{V'^2}$. Since the turbulent velocities do not contribute to the mean weight flow, weight flows computed from impact-tube measurements will be greater than the true mean weight flows. A correction to the computed total-pressure loss based on continuity of mean weight flow therefore is proper since the effective total-pressure loss is based on mean quantities only.

If the boundary layer at the diffuser inlet is not distorted and therefore approaches the usual 1/7-power-law velocity distribution, the $\overline{V'^2}$ component of equation (5) is negligible compared to the V^2 component, and accurate impact-tube measurements and, therefore, accurate mean weight-flow values are obtainable. At the exit of a wide-angle diffuser, however, the boundary layer is usually distorted and mean weight flows computed from impact-tube measurements, contrary to the law of conservation of mass, are greater at the exit than at the inlet. When this condition exists it is reasonable to assume that the $\overline{V'^2}$ component in the boundary layer at the diffuser exit is not negligible.

In the experiments of reference 1, for some of the 0.10-inch-high rough-ledge configurations the weight flows measured at the exit were found to be appreciably greater than those at the inlet. The data plotted in figure 1, which shows the variation of weight flow with inlet airspeed, were taken from this reference and illustrate that discrepancies of the order of 10 to 15 percent were found. Consequently, total-pressure-loss coefficients calculated from these data would be incorrect.

METHOD FOR ESTIMATING CORRECTED TOTAL-PRESSURE-LOSS COEFFICIENTS

If the actual weight flow at any given velocity, the dimensions of the diffuser, and the velocity outside the boundary layer at the diffuser exit are known, a boundary-layer thickness which will satisfy continuity of the mean weight flow can be determined by making a suitable assumption for the velocity distribution and assigning a specific value for the velocity at some particular distance from the diffuser wall. By assuming that the point of zero velocity near the diffuser wall is known, a boundary-layer thickness may be calculated by this procedure and it should not be substantially different from the measured one, provided the assumed velocity distribution fits fairly accurately the probable mean distribution. (In the analysis made herein of the data of reference 1, a linear velocity distribution was assumed. However, for those cases for which the velocity profiles cannot be reasonably matched by a linear velocity distribution, another assumption as to the nature of the profile shape may be made.)

In order to find the corrected total-pressure-loss coefficients, the actual weight flow at any given velocity is first equated to the integral expression for the weight flow at the diffuser exit:

$$W = 2\pi\rho_2 g \int_0^R u_2 r_2 \, dr_2 \tag{6}$$

If the velocity outside the boundary layer U_2 is assumed to be measured accurately by an impact tube and to be constant over that region, equation (6) may be transformed to

$$\delta_{L_2} = \frac{1}{2}\left[3R_2 - \sqrt{3\left(\frac{4W}{\pi\rho_2 g U_2} - R_2{}^2\right)}\right] \tag{7}$$

which gives the boundary-layer thickness as a function of the mean weight flow, the diffuser radius, and the velocity and density outside the boundary layer at the diffuser exit for the assumed linear velocity distribution. The counterpart of equation (7) for separated flow is

$$\delta_{L_2} = \frac{1}{2}\left\{3\left(R_2 - s\right) - \sqrt{3\left[\frac{4W}{\pi\rho_2 g U_2} - \left(R_2 - s\right)^2\right]}\right\} \tag{8}$$

Application of method. - Typical results of the application of the preceding assumptions and equations to the data of reference 1 are given in figure 2. Inasmuch as the point of zero velocity near the wall is assumed to be known, another point on the linear profile (the boundary-layer thickness) can be calculated through use of continuity and the revised values of velocity may be determined at any point. This information, used in conjunction with the density of the free stream at the exit, permits the computation of $\overline{h}_2$ and $\Delta\overline{h}_{0,2}$ through the integration indicated by equation (3). Values of $\Delta\overline{h}_{2,1}/q_{c_1}$ are obtained by dividing the result computed from equation (4) by the inlet impact pressure.

Values of total-pressure-loss coefficient $\Delta\bar{h}/q_{c_1}$ determined in this manner for the three configurations in figure 1 are shown in figure 3. Examination of this figure reveals that the estimated values of $\Delta\bar{h}/q_{c_1}$ are greater than values computed from the experimental data over the speed range. This result was anticipated because, as noted in a preceding section, the values of total pressure recorded by the impact tubes are higher than the mean values and therefore, when integrated across the stream, values of $\Delta\bar{h}/q_{c_1}$ which tend to be low result.

Error introduced by assumption of linear velocity profile. - A check was made with additional data from reference 1 to determine the error introduced by the assumption of a linear velocity profile. Another configuration from reference 1 was selected for which negligibly small discrepancies between inlet and exit weight flows were noted. This configuration, identified as d-1 in reference 1, has four rough ledges of dissimilar heights. The procedure described was applied to the data for this configuration and the results are shown in figure 4. The estimated coefficients are, for this case, almost the same as the values of $\Delta\bar{h}/q_{c_1}$ computed from the original experimental data.

A comparison between the experimentally measured velocity profiles and the assumed linear profiles for this configuration is given in figure 5. The assumed linear distributions are seen to compare reasonably well with the measured profiles for configuration d-1. The values of $\Delta\bar{h}/q_{c_1}$ estimated by the proposed procedure would therefore be expected to be no more than slightly different from those computed from the uncorrected data for this configuration.

The order of magnitude of the error obtained by the linear-profile assumption was determined for several cases for which the linear profile did not provide a good fit to the actual velocity profile. Several velocity profiles were selected from data in references 1 and 3 as typical of those occurring at the exit of diffuser-type components. Figure 6 shows a comparison between the true mean velocity profiles selected for this analysis and the corresponding linear profiles. The linear profile if seen to be a fair approximation to the true profiles for values of H from about 2.6 to 3.4.

Values of $\Delta\bar{h}/q_{c_1}$ were calculated for all the profiles shown in figure 6. For the profiles shown in figures 6(a) to 6(d) the calculations were made for the arbitrary case of $\delta = R/2$ and a representative set of stream conditions from reference 1. Because the value of δ was fixed, it was necessary to allow the weight flow to change for each assumed value of H. The values of W obtained for each of the profiles are indicated in figure 6. Figure 7 shows the variation of the ratio $\frac{\left(\Delta\bar{h}/q_{c_1}\right)_T}{\left(\Delta\bar{h}/q_{c_1}\right)_L}$ with H for the cases investigated.

A further estimate of the order of magnitude of the error obtained by the linear-profile assumption was made for the profiles shown in figures 6(e) and 6(f). For these cases the experimental exit weight flows were greater than those at the diffuser inlet. Accordingly, the velocities near the edge of the boundary layer were assumed to be reasonably accurate and velocity profiles were arbitrarily faired by a trial-and-error process such that the inlet weight-flow values agreed. Values of $\Delta\bar{h}/q_{c_1}$ were calculated for both this faired velocity profile and the linear profile and the values of $\frac{\left(\Delta\bar{h}/q_{c_1}\right)_T}{\left(\Delta\bar{h}/q_{c_1}\right)_L}$ are indicated in figure 7. It should be noted that this procedure implies that the arbitrarily faired curve for the velocity profile is the true profile, and the values of H against which the ratio $\frac{\left(\Delta\bar{h}/q_{c_1}\right)_T}{\left(\Delta\bar{h}/q_{c_1}\right)_L}$ are plotted in figure 7 were obtained from the faired velocity profiles. The results shown in figure 7 indicate that the values of total-pressure-loss coefficient estimated by the proposed method are accurate to within ± 5 percent over a range of boundary-layer shape factors from 1.8 to 4.0.

Remark on application of method. - It should be emphasized that the method proposed is not intended as a substitute for boundary-layer surveys in the experimental determination of diffuser total-pressure-loss coefficients. It should be used as a check for only those cases in which turbulent fluctuating velocities sufficiently influence the diffuser-exit total-pressure observations to result in weight-flow discrepancies.

CONCLUDING REMARKS

A method has been devised for estimating the effect of turbulent velocity fluctuations on diffuser total-pressure-loss measurements as obtained by impact-pressure-tube readings. In the development of this method, continuity of flow is stipulated, and it is assumed that the inlet conditions, the diffuser dimensions, and the width of a separated region, if any, are accurately known, that the flow is symmetrical, and that the velocity outside the boundary layer at the downstream measuring stations is not measurably influenced by the turbulent velocity fluctuations. Only the case of a conical diffuser with incompressible flow is considered, although the method may be readily modified to include effects of compressible-flow conditions.

For cases where the effect of turbulent velocity fluctuations is found to be large, as evidenced by discrepancies between inlet and exit weight flows, the values of total-pressure-loss coefficient calculated from the impact-pressure-tube data are shown to be incorrect. The method compensates for these discrepancies by adjusting the boundary-layer profile. The values of total-pressure-loss coefficient estimated by the proposed method are compatible with flow continuity and are higher than the results obtained from the experimental data. For cases where the effect of velocity fluctuations is small, estimated values of total-pressure-loss coefficient agree well with values obtained directly from experimental data.

The method presented is not intended as a substitute for experimental determination of diffuser total-pressure losses by boundary-layer surveys. It should be used as a check for only those cases in which fluctuating velocities sufficiently influence the total-pressure measurements to produce weight-flow discrepancies.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., July 30, 1953.

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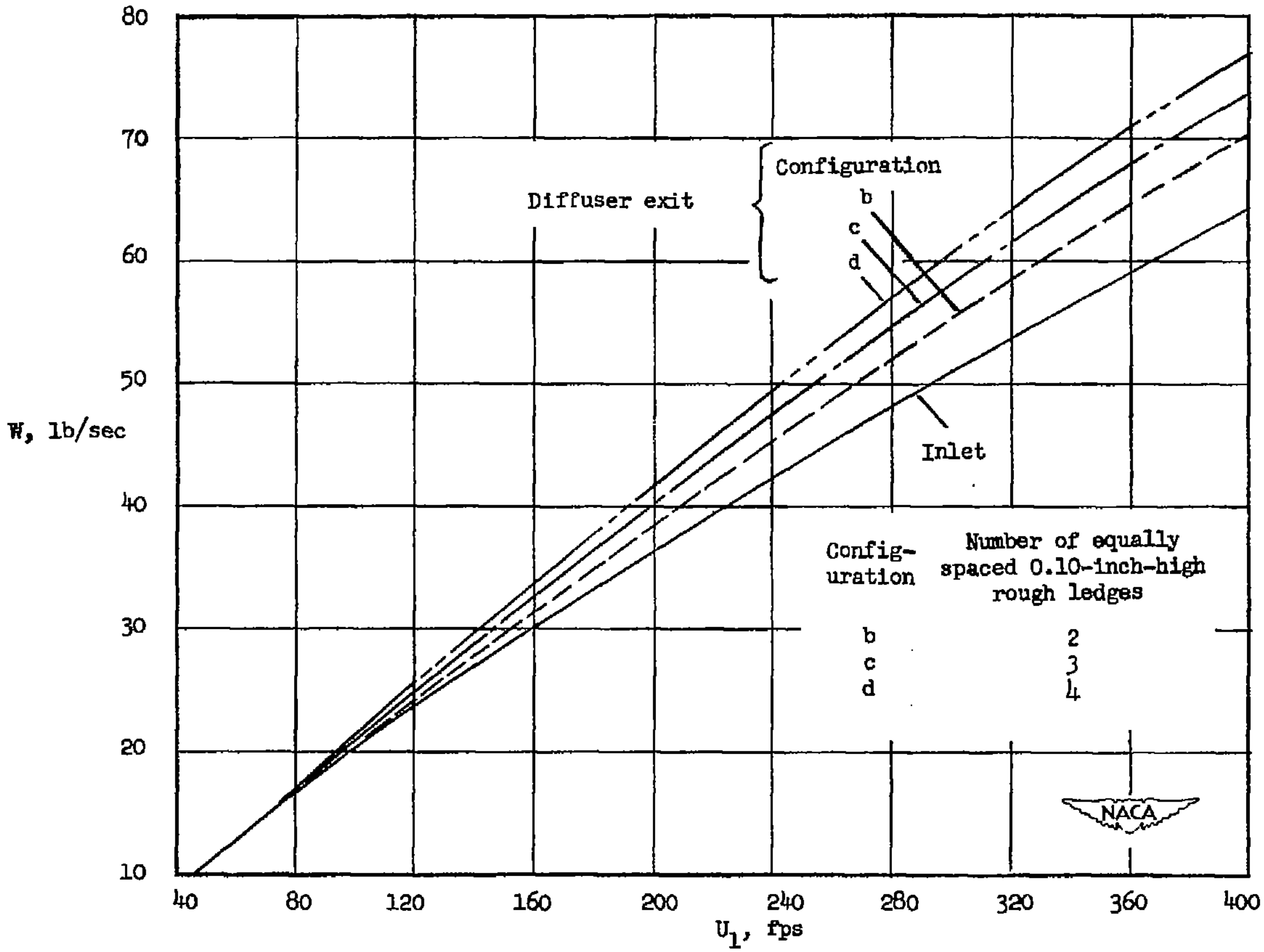

Figure 1.- Example of discrepancies between weight flows computed from inlet and exit impact-pressure measurements (data of ref. 1).

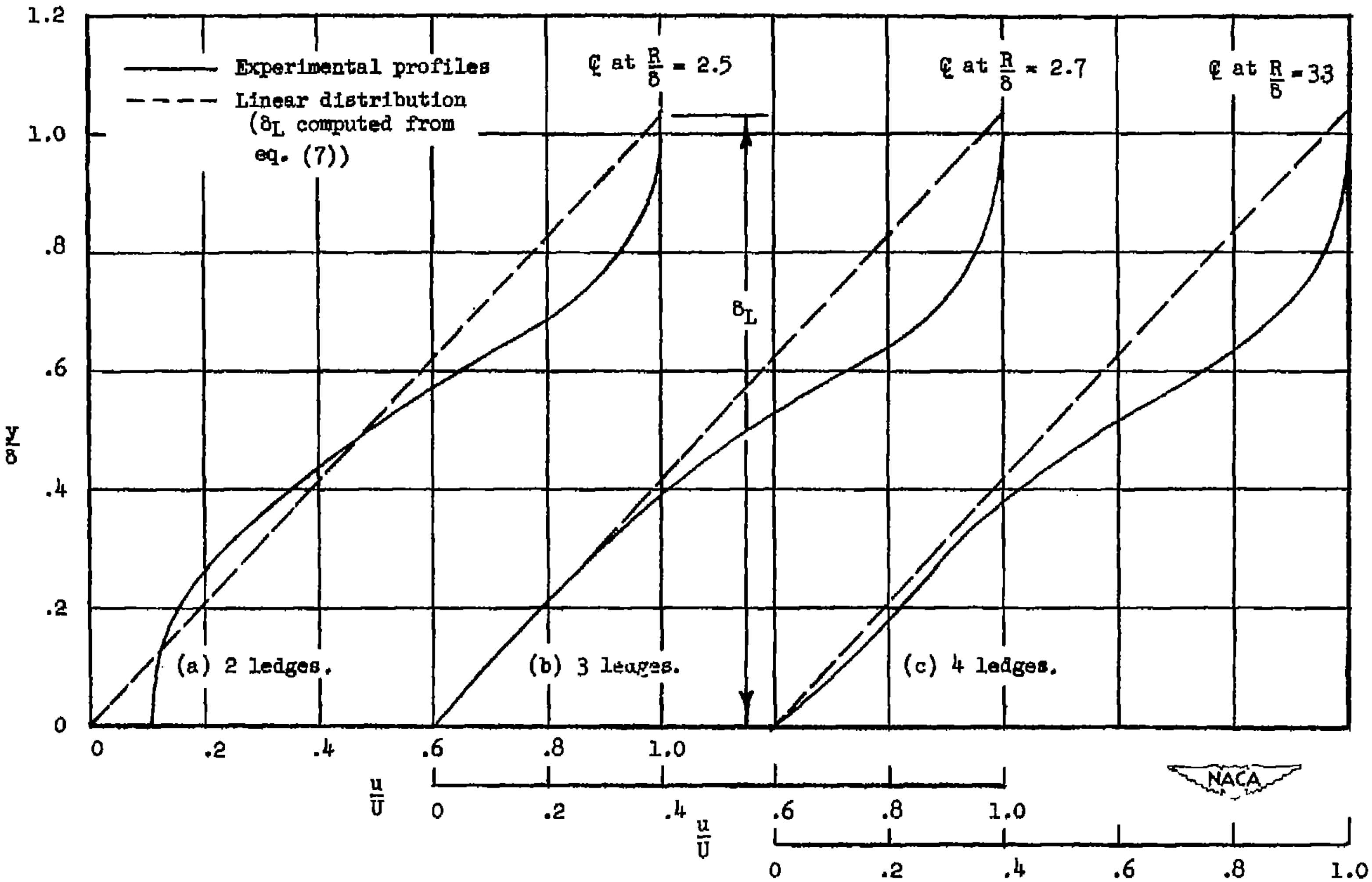

Figure 2.- Comparison of experimental profiles with linear distributions for cases in which observed inlet-exit weight-flow discrepancies were considerable. $U_1 \approx 250$ fps.

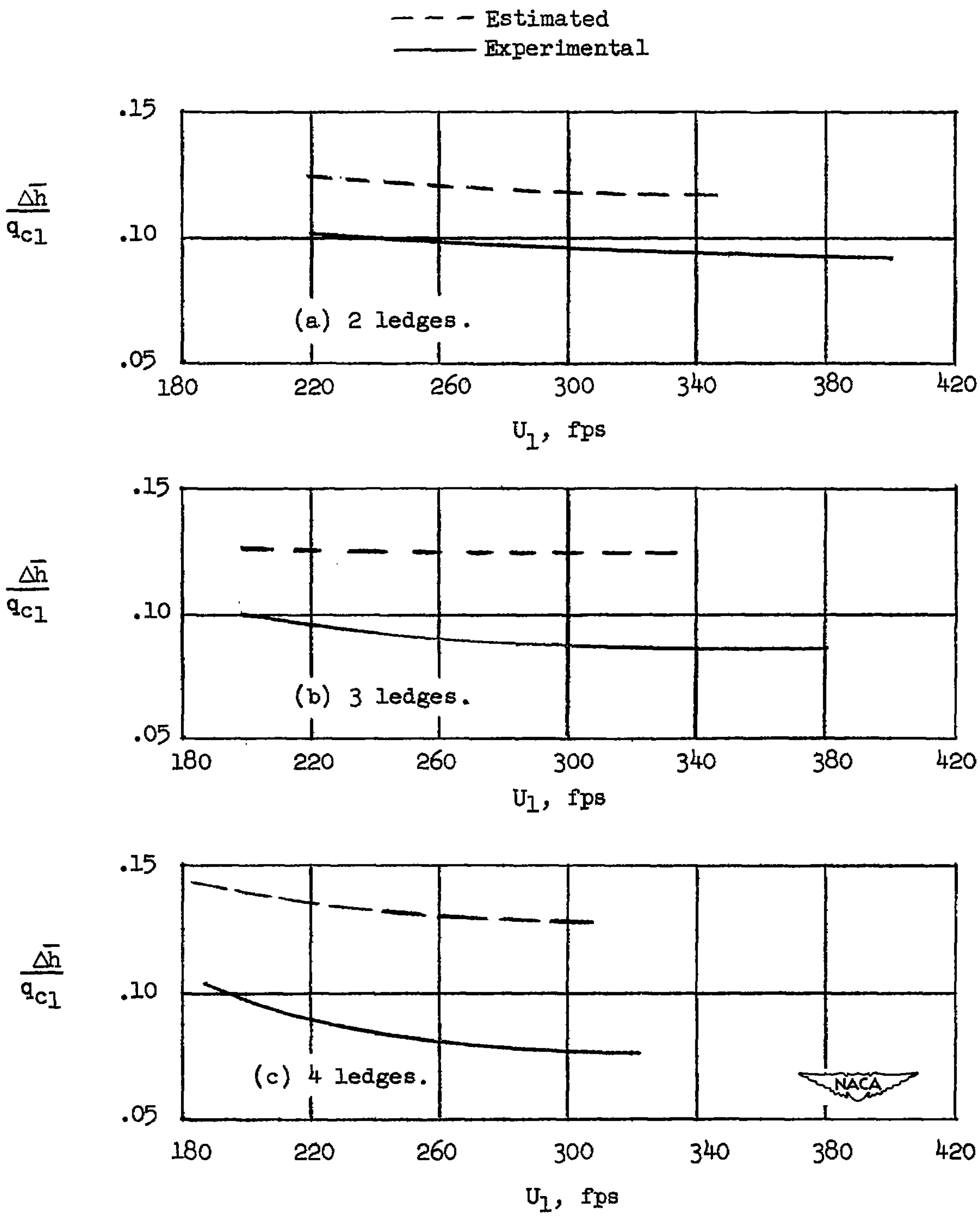

Figure 3.- Total-pressure-loss coefficients computed by conventional interpretation of impact-pressure data compared with values estimated by the method of this paper.

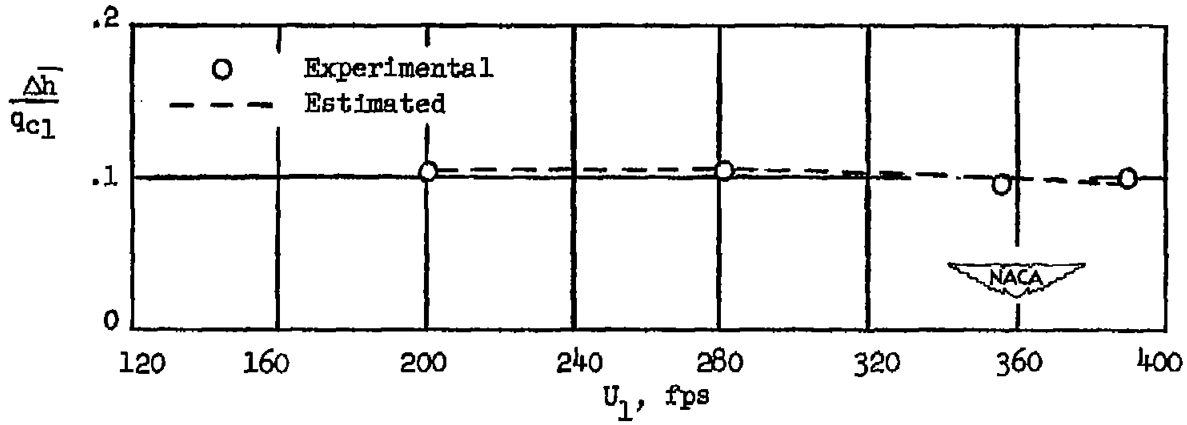

Figure 4.- Total-pressure-loss coefficients computed from pressure data and estimated by present method. (Case of negligible weight-flow discrepancies, configuration d-1 of ref. 1.)

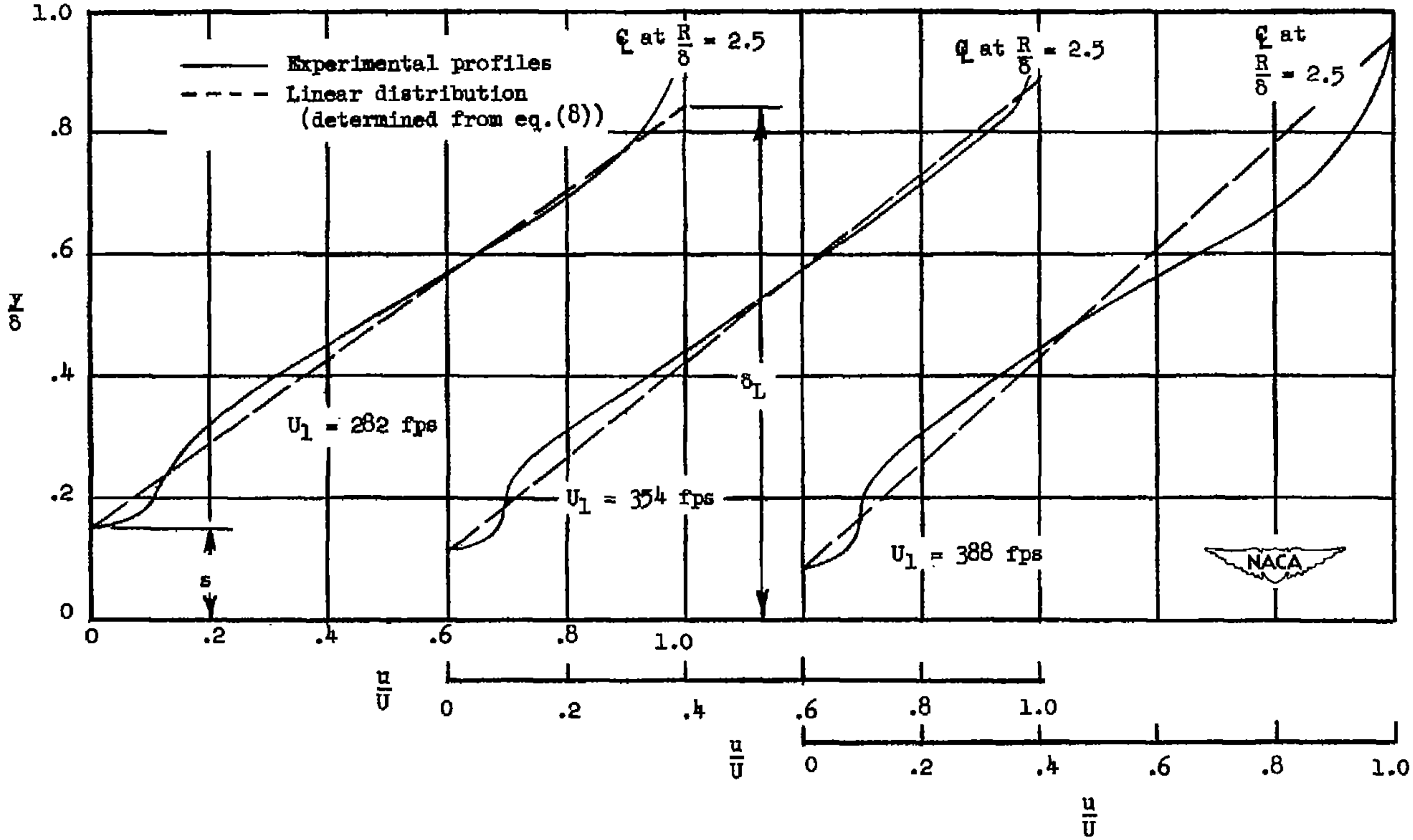

Figure 5.- Comparison of experimental profiles with linear distribution for a case in which observed effects of fluctuating velocities were negligible. (Configuration d-1 of ref. 1.)

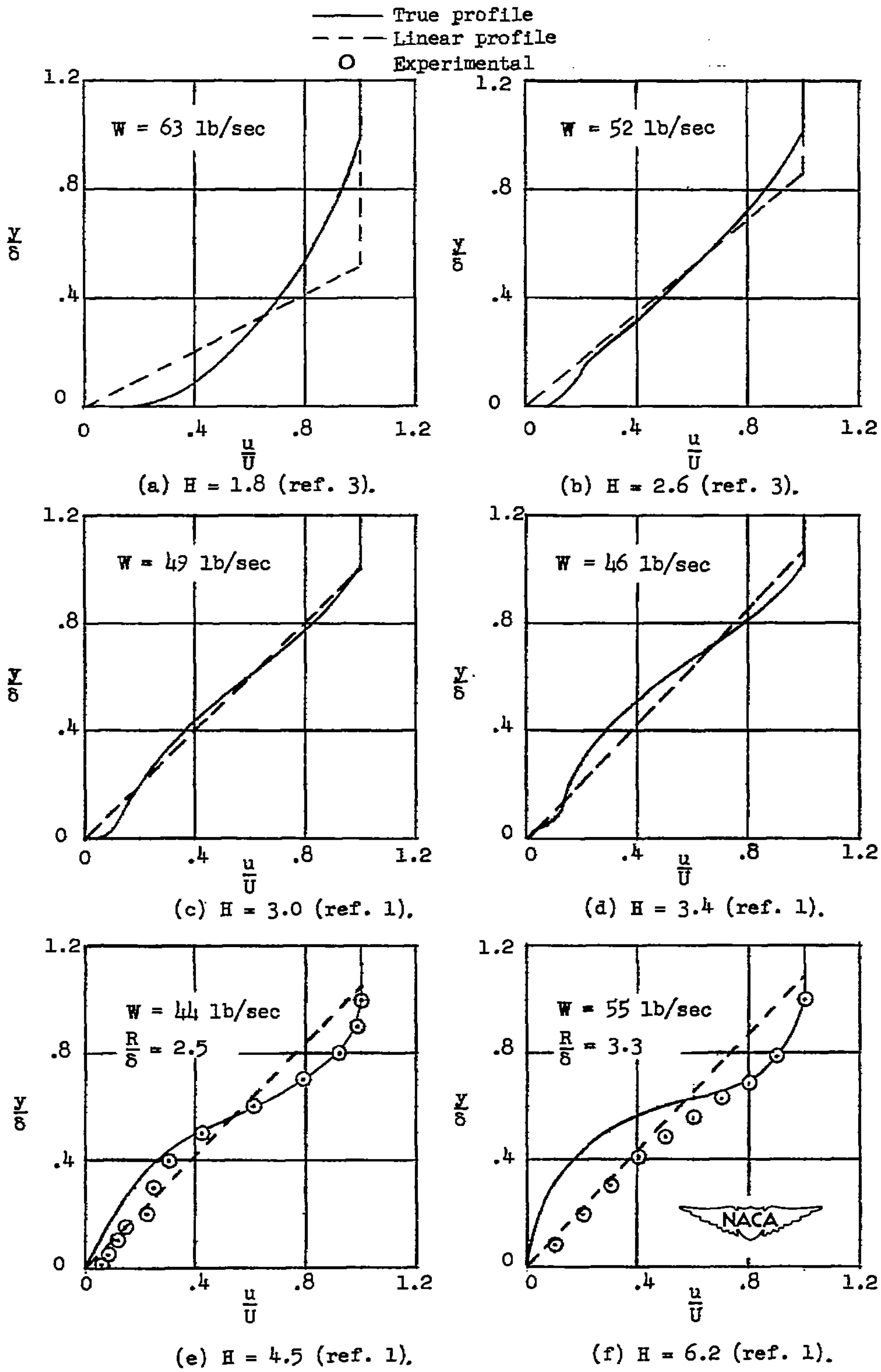

Figure 6.- Comparison of true, linear, and experimental profiles for several values of H.

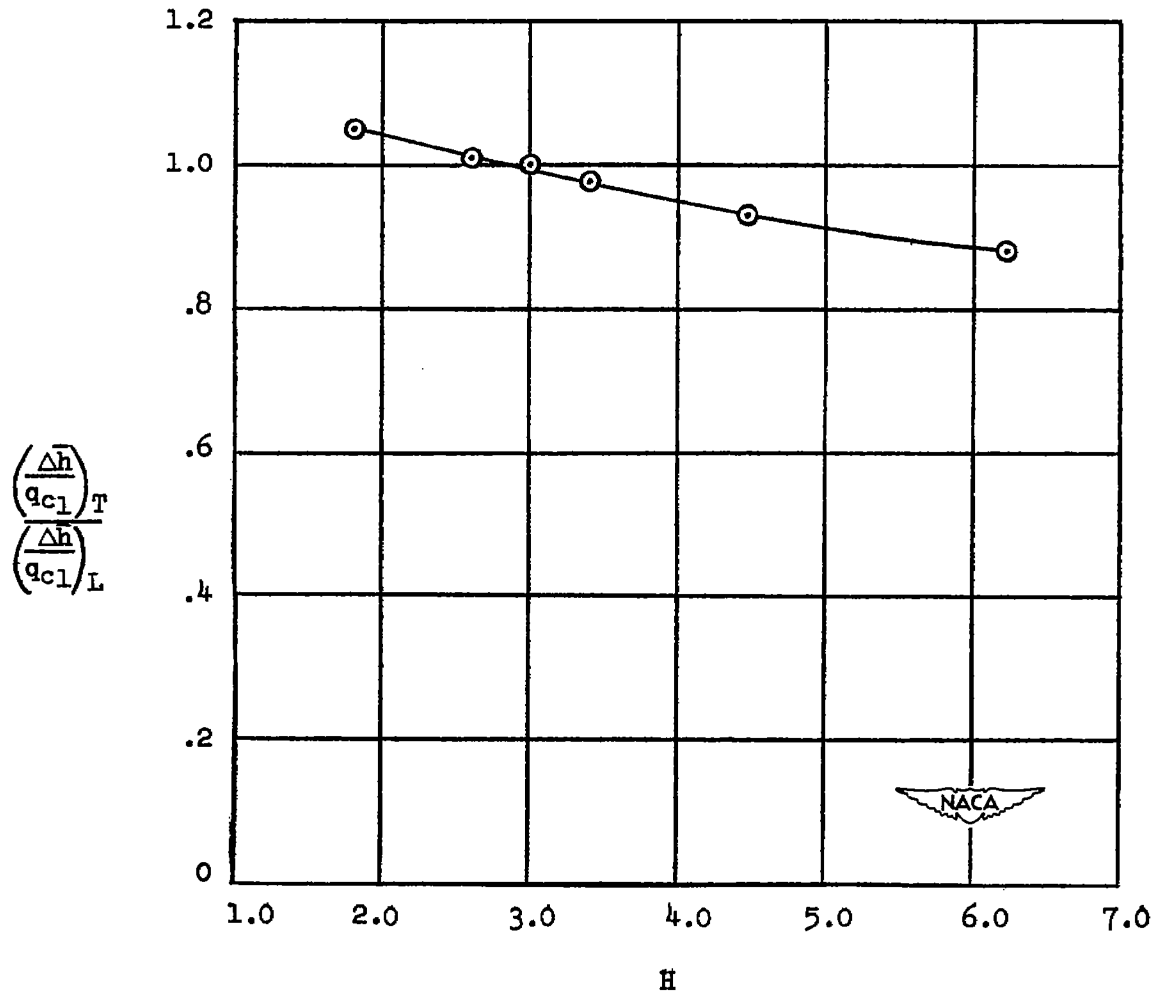

Figure 7.- Variation of $\left(\frac{\Delta\bar{h}}{q_{c_1}}\right)_T \bigg/ \left(\frac{\Delta\bar{h}}{q_{c_1}}\right)_L$ with boundary-layer shape parameter H.

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